RECONCILING SUPERSYMMETRY AND THERMAL LEPTOGENESIS BY ENTROPY PRODUCTION

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The entropy produced in the decays of super-weakly interacting particles may help to reconcile thermal leptogenesis and Big Bang Nucleosynthesis (BBN) in scenarios with gravitino dark matter, which is usually difficult due to late decays of the next-to-lightest supersymmetric particle (NLSP) spoiling BBN. We study this possibility for a general neutralino NLSP. We discuss the constraints on the entropy-producing particle, considering as an example the saxion from the axion multiplet. We show that, in addition to enabling a solution of the strong CP problem, it can indeed produce a suitable amount of entropy.

1 The Gravitino Problem

The tiny but non-zero neutrino masses, which constitute the first solid evidence for physics beyond the Standard Model (SM), find a natural explanation in the see-saw mechanism.[1,2,3,4,5] In this setup the SM is extended by gauge-singlet neutrinos with very large masses. The C- and CP-violating decay of these heavy neutrinos in the early universe can provide the observed baryon asymmetry via leptogenesis[6] as an almost free by-product. The CP asymmetry of the decays

$$\epsilon = \frac{\Gamma(\nu_\mathrm{R} \to \ell H) - \Gamma(\nu_\mathrm{R} \to \overline{\ell}\,\overline{H})}{\Gamma(\nu_\mathrm{R} \to \ell H) + \Gamma(\nu_\mathrm{R} \to \overline{\ell}\,\overline{H})} \tag{1}$$

creates a lepton asymmetry, which is afterwards converted into a baryon asymmetry $\eta_\mathrm{B} = \frac{n_\mathrm{B}}{n_\gamma} \propto |\epsilon|$ by sphaleron processes.[7] We denote the lightest of the heavy neutrinos by ν_R and its mass by M_R. For hierarchical heavy neutrino masses and no fine-tuning, the CP asymmetry is limited by[8]

$$|\epsilon| < \frac{3}{16\pi} \frac{M_\mathrm{R}\sqrt{\Delta m^2_\mathrm{atm}}}{v^2} \,. \tag{2}$$

Using the mass squared difference Δm^2_atm measured in atmospheric neutrino oscillations, the Higgs vacuum expectation value v, the observed baryon asymmetry $\eta_\mathrm{B} \simeq 6 \cdot 10^{-10}$, and other known quantities then leads to the lower limit $M_\mathrm{R} \gtrsim 2 \cdot 10^9$ GeV.[9]

The only price to pay for all the baryons is a mechanism producing the heavy neutrinos in the first place. In the simplest scenario, thermal leptogenesis, the temperature is larger than M_R, so the heavy neutrinos are abundantly produced, since they are in contact with the thermal bath via their Yukawa couplings. Consequently, thermal leptogenesis requires a sufficiently high reheating temperature after inflation,

$$T_\mathrm{R} \gtrsim M_\mathrm{R} \gtrsim 2 \cdot 10^9 \text{ GeV} \,. \tag{3}$$

This scenario does not address the biggest theoretical problem of the SM, the hierarchy problem. This problem is elegantly solved by supersymmetry (SUSY), which in turn offers a natural way to include gravity in the form of supergravity. Within this theory, the large temperature in the early universe also leads to a thermal production of gravitinos, the superpartners of the graviton. Their relic density is approximately[10,11]

$$\Omega_{3/2}^{\mathrm{tp}} h^2 \simeq 0.11 \left(\frac{T_{\mathrm{R}}}{2 \cdot 10^9\,\mathrm{GeV}}\right) \left(\frac{67\,\mathrm{GeV}}{m_{3/2}}\right) \left(\frac{M_{\widetilde{g}}}{10^3\,\mathrm{GeV}}\right)^2 . \tag{4}$$

Thus, the observed dark matter abundance $\Omega_{\mathrm{DM}} h^2 \simeq 0.11$ is compatible with the reheating temperature required by thermal leptogenesis both for a gravitino lightest superparticle (LSP) with a sufficiently large mass $m_{3/2} \gtrsim 60\,\mathrm{GeV}$ and for a heavier non-LSP gravitino.

However, as it interacts only via gravity, a non-LSP gravitino has a long lifetime between, very roughly, $10^{-2}\,\mathrm{s}$ and several years. Consequently, it decays during or after Big Bang Nucleosynthesis (BBN), releasing energetic decay products that destroy the light nuclei produced by BBN.[12,13] The observed primordial element abundances limit the gravitino density and thus the reheating temperature. The result is $T_{\mathrm{R}} \ll 10^8$ GeV, unless $m_{3/2} \gg 1$ TeV.[14] So thermal leptogenesis is not possible for an unstable gravitino with a mass similar to the other superparticle masses, as expected in most scenarios of SUSY breaking.

Let us therefore concentrate on the case of a gravitino LSP with a mass around 100 GeV. For conserved R parity, the gravitino is now stable and does not cause any problems. However, the next-to-LSP (NLSP) can only decay to the gravitino via gravity. Thus, it is long-lived and its decay products threaten the success of BBN. If the NLSP relic density is determined by the standard freeze-out mechanism, the resulting changes of the primordial abundances are incompatible with observations in the Minimal Supersymmetric Standard Model (MSSM) with TeV-scale SUSY, with the exception of very small corners of the parameter space. Consequently, the gravitino problem survives in the form of the NLSP decay problem.

2 Entropy Production

We consider one of the many approaches to solve the gravitino problem, the possibility that a large amount of entropy is produced after the freeze-out of the NLSP, diluting its density by a factor Δ.[15,16,17,18] This reduces the impact of the NLSP decays on BBN, possibly making it compatible with observations.

The entropy can stem from the decay of a non-relativistic particle ϕ. The energy density of such a particle only decreases as $\rho_\phi \propto R^{-3}$, where R is the scale factor of the universe, while the energy density of radiation decreases faster, $\rho_{\mathrm{rad}} \propto R^{-4}$. Consequently, if ϕ is sufficiently long-lived, ρ_ϕ will equal ρ_{rad} at some temperature $T_\phi^{=}$, and it will dominate the energy density of the universe afterwards. Eventually, the particle decays into radiation at a temperature T_ϕ^{dec}, increasing the entropy per comoving volume by a factor[19,20]

$$\Delta \simeq 0.75\,\frac{T_\phi^{=}}{T_\phi^{\mathrm{dec}}} \tag{5}$$

and thus diluting all previously produced relic abundances by the same factor.

We require radiation domination at the time of NLSP freeze-out, so that the standard computation of its thermal relic density is valid. This means that $T_\phi^{=} < T_{\mathrm{NLSP}}^{\mathrm{fo}} \sim \frac{m_{\mathrm{NLSP}}}{25}$. The decay of ϕ has to happen before BBN to avoid changing the primordial abundances, $T_\phi^{\mathrm{dec}} > T_{\mathrm{BBN}} \sim 4\,\mathrm{MeV}$. This leads to the upper bound

$$\Delta \lesssim 0.75 \cdot 10^3 \left(\frac{m_{\mathrm{NLSP}}}{100\,\mathrm{GeV}}\right) . \tag{6}$$

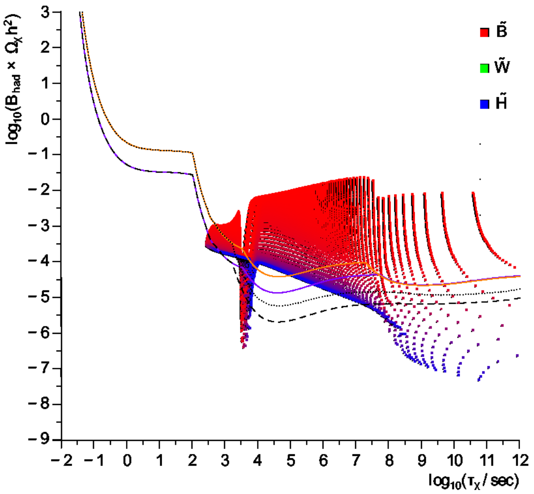

Figure 1: Lifetime versus hadronic energy release of a bino-higgsino neutralino compared with the hadronic BBN constraints [23] for the case of a 100 GeV gravitino mass and a dilution factor $\Delta = 10^3$. All points above the uppermost line are excluded, while those between the curves should not be considered as strictly excluded. The neutralino mass increases from right to left. Its composition varies from bino at the top to higgsino at the bottom, with the colors giving the dominant component (from [18]).

The amount of entropy production is also limited by leptogenesis, since it dilutes the baryon asymmetry by a factor Δ, too. According to Eq. 2, this has to be compensated by increasing M_R by the same factor. However, for very large values of M_R the baryon asymmetry is strongly reduced by washout processes.[21] This places an upper limit on M_R and thus on Δ. We estimate $\Delta \lesssim 10^3 \ldots 10^4$, which roughly coincides with the bound in Eq. 6 for NLSP masses around the electroweak scale. Note that the increase of M_R raises the lower limit on the reheating temperature by a factor Δ as well. Assuming $T_\mathrm{R} \sim M_\mathrm{R}$, this exactly compensates the dilution of the gravitino density, so we still obtain the correct dark matter density.

As a concrete example, let us consider the constraints from BBN on a neutralino NLSP for a gravitino LSP mass of 100 GeV and a dilution factor $\Delta = 10^3$. Performing a scan over the low-energy gaugino and higgsino mass parameters allowed by LEP and corresponding to neutralino masses up to 2 TeV, we arrive at the points shown in Fig. 1 for the case of a neutralino whose main components are the bino and the higgsinos. The horizontal axis of the plot is the neutralino lifetime. The vertical axis is its relic density multiplied by the hadronic branching ratio and thus determines the energy released in the form of hadrons. See [22] for details of the calculation of these quantities. The curves in the figure are the bounds from BBN on hadronic energy release.[23] All points above the uppermost line are definitely excluded, while those between this line and the dashed line may be allowed. Everything below the dashed line is definitely compatible with current observations.

We see that even with considerable entropy production a large part of the parameter space remains excluded. In particular, a neutralino with dominant bino component is only possible for quite small lifetimes correponding to masses above 1 TeV. However, unlike in the case without entropy production, we do find allowed regions now. There are states with comparable bino and higgsino components and $m_\mathrm{NLSP} \simeq 230$ GeV violating only the less conservative BBN bound. Neutralinos that are mainly higgsino satisfy even these constraints, if they are lighter than 250 GeV. They can be almost as light as the gravitino. Thus, we have arrived at a scenario where thermal leptogenesis is possible and the gravitino or NLSP decay problem is solved.

A change of Δ shifts all points vertically by a corresponding factor. Therefore, it is straightforward to infer the constraints for arbitrary Δ from the results shown here. In [18] other possible neutralino compositions and also the BBN constraints from electromagnetic energy release have been discussed in detail. In particular, it turned out that a neutralino with a large wino component is also possible.

3 Candidates for the Entropy Producer

Let us next discuss candidates for the field ϕ producing the entropy. A list of general requirements is shown in Tab. 1. Most of them are already clear from the discussion in the previous section. Requirement vii is that the presence of ϕ be compatible with gravitino dark matter. This would be violated, for example, if the gravitino could decay into ϕ with a lifetime shorter than the age of the universe t_0. The last requirement concerns other particles that have to be introduced together with ϕ, such as its superpartners. They must not violate ii or vii, must not produce many NLSPs or gravitinos in their decays (v, vi) and must not introduce new problems on their own.

In fact, the requirements in the table either have to be fulfilled or are generically fulfilled in any scenario containing long-lived particles. As a consequence, the solution of the generic problems of long-lived particles may automatically lead to the desired entropy production.

One potential candidate for the entropy producer exists if the strong CP problem is solved by the Peccei-Quinn mechanism.[24,25] This mechanism involves the axion supermultiplet containing two real scalars, the axion and the saxion ϕ_{sax}, as well as their superpartner, the axino $\widetilde{a}$. Their interactions with the MSSM particles are suppressed by the Peccei-Quinn scale $f_a \gtrsim 6 \cdot 10^8\,\mathrm{GeV}$, which makes them long-lived.

In particular, the saxion is a suitable candidate to produce entropy, since it has even R parity and therefore can decay into SM particles without producing superparticles. If its dominant decay mode is into a pair of gluons, the decay temperature is [26]

$$T_{\mathrm{sax}}^{\mathrm{dec}} \simeq 53\,\mathrm{MeV} \left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right) \left(\frac{m_{\mathrm{sax}}}{1\ \mathrm{TeV}}\right)^{\frac{3}{2}} . \tag{7}$$

Thus, a decay shortly before BBN is possible.

If the saxion is produced in thermal equilibrium, its density starts to dominate at

$$T_{\mathrm{sax}}^{=} \simeq 1.6\ \mathrm{GeV} \left(\frac{m_{\mathrm{sax}}}{1\ \mathrm{TeV}}\right) . \tag{8}$$

Together with Eq. 5, this yields

$$\Delta \lesssim 55 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{\frac{2}{3}} . \tag{9}$$

Table 1: List of requirements for our scenario of entropy produced by ϕ to dilute the NLSP (from [18]).

No.	Requirement	Reason or Comment
i	$T_\phi^{\mathrm{dec}} < T_{\mathrm{NLSP}}^{\mathrm{fo}}$	dilute Ω_{NLSP}
ii	$T_\phi^{\mathrm{dec}} > T_{\mathrm{BBN}}$	do not spoil BBN
iii	$\frac{\rho_\phi}{\rho_{\mathrm{rad}}}(T_\phi^{\mathrm{dec}}) > 1$	needed for $\Delta \gg 1$
iv	$\frac{\rho_\phi}{\rho_{\mathrm{rad}}}(T_{\mathrm{NLSP}}^{\mathrm{fo}}) < 1$	for standard NLSP freeze-out
v	$\mathrm{Br}(\phi \to \mathrm{NLSP}) \simeq 0$	avoid NLSP decay problem
vi	$\mathrm{Br}(\phi \to \mathrm{gravitino}) \simeq 0$	avoid gravitino overproduction
vii	e.g., $\tau_{3/2} \gg t_0$	compatibility with gravitino dark matter
viii	ii and v–vii	for by-products; no new problems

This dilution factor is much smaller than the value $\Delta = 10^3$ considered previously and in fact inconsistent with gravitino dark matter, since saxions enter thermal equilibrium only if $T_{\mathrm{R}} \gtrsim f_a$. Besides, the decays of axinos would produce a disastrous amount of NLPSs for $f_a \gtrsim 10^{10}$ GeV.

We have to conclude that the thermally produced saxion is not suited to produce a sufficient amount of entropy. While it satisfies all the requirements of Tab. 1 (if we choose $f_a \lesssim 10^{10}$ GeV to fulfill viii), the resulting dilution factor is simply too small. This can be traced back to two conflicting requirements: on the one hand sufficient saxion production requires sufficiently strong couplings (small f_a), while on the other hand sufficiently late decay requires weak couplings (large f_a), where later decay corresponds to more entropy production. In the considered case, the allowed parameter ranges fail to overlap. Using simple estimates we can generalize this negative conclusion to a generic thermally produced particle.[18]

Fortunately, we do not have to rely on thermal production of saxions. It can be abundantly produced in coherent oscillations about its potential minimum, if the saxion field is displaced from this minimum during inflation. In this case, Eq. 8 changes to [27]

$$T^{=}_{\mathrm{sax}} \simeq 6.4\,\mathrm{GeV} \left(\frac{m_{\mathrm{sax}}}{1\ \mathrm{TeV}}\right)^{\frac{1}{2}} \left(\frac{f_a}{10^{14}\ \mathrm{GeV}}\right)^2 \left(\frac{\phi^{\mathrm{i}}_{\mathrm{sax}}}{f_a}\right)^2 , \qquad (10)$$

where $\phi^{\mathrm{i}}_{\mathrm{sax}}$ denotes the initial amplitude of the oscillations. Now production and decay are decoupled, so we are able to choose parameter values that yield a large dilution factor saturating the upper bound of Eq. 6. For example, this is the case for $m_{\mathrm{sax}} \sim 10$ GeV, $m_{\widetilde{a}} \sim 1$ TeV, $f_a \sim 10^{10}$ GeV, and $\phi^{\mathrm{i}}_{\mathrm{sax}} \sim 10^4 f_a$.

4 Conclusions

We have considered the early universe in a scenario where a relatively heavy gravitino is the LSP and forms the dark matter, enabling a reheating temperature large enough for thermal leptogenesis. In order to prevent late NLSP decays from ruining the success of BBN, we have required a dilution of the NLSP relic density by a factor $\Delta \sim 10^3$. This dilution can be caused by the entropy from the decay of a long-lived non-relativistic particle. A diluted neutralino NLSP can be compatible with BBN, if it has a large higgsino or wino component.

We have discussed the general requirements for the entropy-producing particle. Afterwards, we have studied the saxion from the axion supermultiplet as a specific example. We have found that the saxion will not have the desired effects if it is produced only thermally. However, non-thermal production in coherent oscillations overcomes this problem and allows the saxion to produce a large amount of entropy.

Thus, we may conclude that we have arrived at a scenario with a completely consistent cosmology. Thermal leptogenesis produces the correct baryon asymmetry, the density of the gravitino dark matter is compatible with the observed value, and BBN works as successfully as in the Standard Model. In addition, the strong CP problem is solved by the Peccei-Quinn mechanism.

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